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FRONT COVER: This photograph of the big bang contains the largest and the most distant structures ever detected. It is a microwave map of the full sky at 53 GHz based on data from the Differential Microwave Radiometer aboard the COBE satellite. The horizontal band is contamination from our galaxy.

The red and blue spots are temperature fluctuations on an angular scale of ~ 10 degrees and indicate density inhomogeneities which acted as the seeds for the gravitational collapse of great walls and filaments of galaxies. Picture courtesy of NASA and George Smoot.

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SCIENTIFIC CONTROVERSIES IN TEACHING SCIENCE

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Nahum Kipnis was born and educated in the former USSR, where he received an MSc degree in physics and mathematics. He taught high school and college physics, and did research in experimental physics and the history of science. In 1979 he emigrated to the USA. In 1984 he received a PhD degree in history of science from the University of Minnesota. The thesis was published as History of the Principle of the Interference of Light (Birkhaser, Basel, 1991). His historical research focuses on optics, electricity, X rays, radioactivity, and others. In science education, he developed a new technique for improving the learning of science by combining the history of science with investigative experiments, which he taught to to science teachers at The Bakken Museum in Minneapolis. This work has been written up in the book Rediscovering Optics (BENA Press, Minneapolis, 1992).

INTRODUCTION

"What is science?" This question is not necessarily an abstract one to preoccupy a handful of scholars. It is a very practical question parents ask when hearing that their children—high school graduates —want to go into "science" "Does my boy or girl have the qualities to succeed in science? Is science a profession a diligent student can learn, or a special gift is required to study science, such as is required for singing, for instance? Perhaps he or she had better go to study law or medicine?"

The work of a lawyer or a physician is visible to public, and there is a sense of understanding what these professionals do. Not so about scientists. The word "science" usually flashes in people's minds only when a controversial issue related to science is raised in the media, such as building a space station or genetic engineering. When hearing arguments for and against such a project people ask themselves how much in this debate is science and how much is special groups' interests. When big money is involved, or there are concerns with health, the environment, or even survival of the human species, it is difficult to separate scientific arguments from social, political, religious and other ones.

Figure 1

A historian of science would suggest that it is easier to understand the nature of science or the work of scientists, if we turn to scientific debates of the past: it is easier to judge the arguments when one understands the subject matter.

Normally, individual scientists' arguments for and against each theory remain unknown to but a few, but once in a while some scientists decide to take them out into a public forum. These cases are precious, because they offer an opportunity to learn how scientists make their judgements, what criteria they use, and the like.

I will discuss today two examples of such scientific controversies, the debate on the "animal" electricity and the debate on the nature of the voltaic pile. Both are associated with the name of Alessandro Volta and, in particular, with his discovery of the electric battery, the bicentennial of which is being celebrated this year around the world.

The "animal" electricity

This controversy began in 1792, after publication of the discovery by Luigi Galvani (1737-1798), Professor of Anatomy and Obstetrics at the University of Bologna . For more than 10 years, Galvani studied electrical stimulation of animal organs, especially a frog's preparation of hind legs and part of the vertebra (Fig. 1). It had been known for quite a while that a muscle twitched if one pricks the corresponding nerve with a sharp needle, or places a grain of salt on it, or touches the nerve with a hot object. Then it was found that touching the nerve with a conductor carrying static electricity produced even more powerful contractions, and several physiologists began to study electrical stimulation systematically. The view of that time was that muscles move when an agent called "nervous fluid" flows from the brain to the muscle through a nerve. According to one of the theories, shared by Galvani, this fluid was of an electrical nature. The facts in favour of this hypothesis were: 1) the high speed of the muscular reaction; 2) the existence of electric fish and 3) the possibility of electric stimulation of animals. Once Galvani observed contractions when a scalpel touched a frog at the same time as an electrical machine unconnected to it produced a spark. Galvani thought that if electrical stimulation can take place at a distance, then atmos-

pheric electricity can do it too. Indeed, he observed that a frog's preparation placed outside twitched during a thunderstorm. When he hung the preparation on the grill by means of a hook attached to the vertebra, the legs twitched even in serene weather. A closer inspection showed that the convulsions occurred only when the legs touched the grill. To eliminate atmospheric electricity, Galvani brought the frog inside his room and touched both the nerve and the muscle with an iron arc: the contractions resumed.

To prove that the stimulation was not mechanical, he laid down the nerve and the muscle on two metal plates and brought the arc in touch with these plates rather than with the tissues: the contractions continued . The stimulation appeared to be electrical in nature, because if the connecting arc included a piece of non-conducting material, such as glass, there was no twitching. To eliminate static electricity coming from his body or the table, Galvani provided the arc with a glass handle and made the support for the frog from a conducting material. Galvani concluded that since the stimulating agent was electricity and it was neither static nor atmospheric electricity, it had to be a new kind of electricity, and probably it was "animal" electricity.

To explain the new phenomena, which became known as "galvanic", Galvani argued that due to life processes a disbalance of electricity is created between a nerve and a corresponding muscle, as in a Leyden jar. When the two are connected by a good conductor, a "discharge" occurs, and the flow of electricity stimulates contractions.. According to Galvani, this experiment (and some others) proved that animal electricity is not limited to certain fish but exists in every animal body.

The "contact" electricity

Galvani's theory immediately prompted several objections. One was that since both muscles and nerves are conductors, they cannot make a Leyden jar. To counter this, Galvani invented an oily substance that supposedly insulated the sciatic nerve from the muscle. Another objection was that convulsions were much stronger when the arc consisted of two different metals rather than a single one. This circumstance appeared crucial to Alessandro Volta (1745-1827), Professor of Physics at the University of Pavia. Volta agreed that the phenomenon was electrical but he assumed the main source of electricity to be outside, in the contact of different metals, and the frog was merely a conductor.

Being unable to explain convulsions produced with a single metal, Volta maintained for a while the "animal" electricity together with his "contact" electricity . Then in 1794 he discovered experimentally that a difference in temperature or polish at the ends of a wire was sufficient to excite contractions. Thus, he concluded, since a single heterogeneous wire could be treated as two different metals, the contact electricity alone could explain all phenomena,. Giovanni Aldini (1762-1834), Professor of Physics at the University of Bologna and Galvani's nephew, countered this argument with a new experiment . He showed that mercury free of the heterogeneity described by Volta did produced contractions. Another strong blow to Volta's theory came from Galvani's and Aldini's exper-

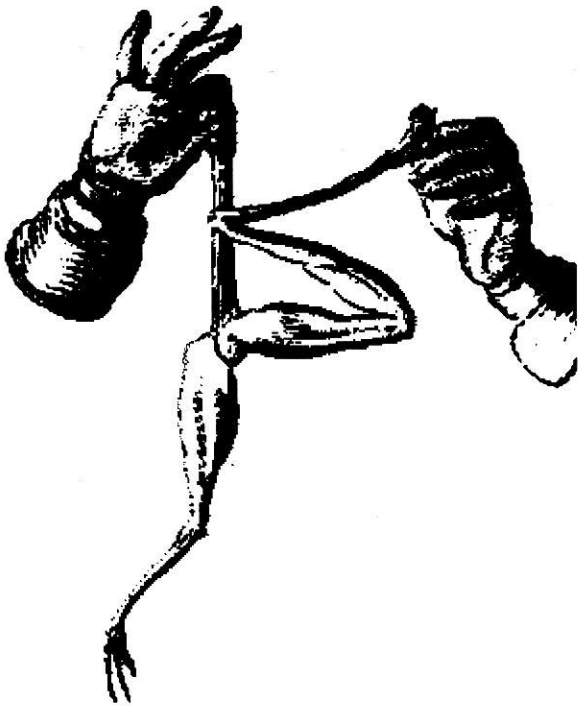

Figure 2

iment in which contractions occurred when a nerve directly touched the muscle without any intermediaries (the so-called "all-animal" circuit) (Fig.2)

First, Volta tried to find a flaw in the opponents' experiments, such as mechanical pressure or a chemical difference at the ends of the connecting arc, but eventually he decided to modify his own theory. According to the new more general theory, electricity can be moved by a contact of any two different substances. The greatest electromotive force is created by a contact of different metals and some other solid bodies; a less vigorous effect was produced by a contact of a metal with a liquid or a wet substance; and the weakest of all was a contact of two liquids or wet substances.

Although Volta's new theory explained all galvanic phenomena, this generality was a sign of weakness rather than strength. Indeed, his statement that any three conductors of the second class created galvanic electricity could not be independently verified, for the only experiment supporting it - the "all-animal circuit" - was the one that the hypothesis was created to account for. Besides, Volta had a difficulty in combining this generality with the fact that the contractions produced by two different metals and a liquid were much stronger than the rest. Actually, he opened a path for returning to his original theory that weakest contractions may result from internal animal electricity while the stronger ones came from external electricity. At the time, no one utilised this opportunity, but fifty years later this theory began to gain strength.

By 1795, Volta realised that he could not fully establish the existence of the "contact" electricity without eliminating the "animal electricity". The main difficulty with this was that the frog's preparation was the only available sensitive detector of galvanic electricity: one could always say that electricity

responsible for the contractions came from the frog itself rather than from the external part of the circuit. Thus Volta decided to replace the frog with an electrometer provided with a multiplier (either a condenser or a doubler).

He soldered copper and zinc rods to one another. Holding its zinc end in his hand he brought the copper end in touch with a copper disk of a condenser: the electrometer showed a negative charge. To Volta, this proved that a contact of zinc and copper makes copper negative with respect to zinc, or that electricity moves across the contact from copper to zinc. However, when he reversed the bi-metal, touching the condenser with zinc, the electrometer showed no charge instead of the expected positive one. Volta explained the result by an interference of another contact, between the condenser plate and the zinc rod: two copper objects adjacent to zinc pushed electricity in the opposite directions, and so electricity did not move. To prove this, he placed a piece of wet cardboard between zinc and condenser: now the electrometer was charged positively. According to Volta, water eliminated the effect of the second copper-zinc contact without creating an electromotive force of its own at its contact with a metal. Since the electrometer showed the same magnitude of tension with water and without, Volta concluded that water does not play any significant role in creating electricity. Although he had no means to prove this, this statement was accepted without any challenge.

Volta's hope that the electrometer experiment would provide the decisive proof of his theory did not materialise, in part because the electricity produced by a contact was so weak that it could have been confused with "spontaneous" electricity produced by multipliers during their operation. Volta however remained convinced of the truth of his theory, which led him in December 1799 to one of the greatest discoveries of the nineteenth century: an electric pile.

The Pile

In March 1800 Volta described it in a letter sent to the Royal Society of London, where it was read on June 26. The apparatus consisted of many similar components—"couples"—consisting of two different metals such as silver and zinc or copper and zinc (originally they used coins) and a wet cardboard. In one form of this apparatus (a "pile") all these components ("couples") made up a column arranged from the bottom up, for instance, as follows: copper, zinc, cloth, copper, zinc, cloth, etc. Another version of this apparatus, called a "chain of cups", consisted of a number of non-metal cups filled with salt water, each having a zinc and a copper plate immersed in water. The cups were arranged so that the zinc of one cup was connected to the copper of another cup, and so on (Fig. 3).

Volta observed that when the number of couples was sufficiently high, the pile produced a shock similar to that of a Leyden jar. In addition to shock, the apparatus could affect an electrometer and produce an electric spark, although these actions were less pronounced than the shock. For these reasons, Volta compared his apparatus to a battery of Leyden jars, "weakly charged" but of an "immense capacity". However, he emphasises two important differences between them: 1) the

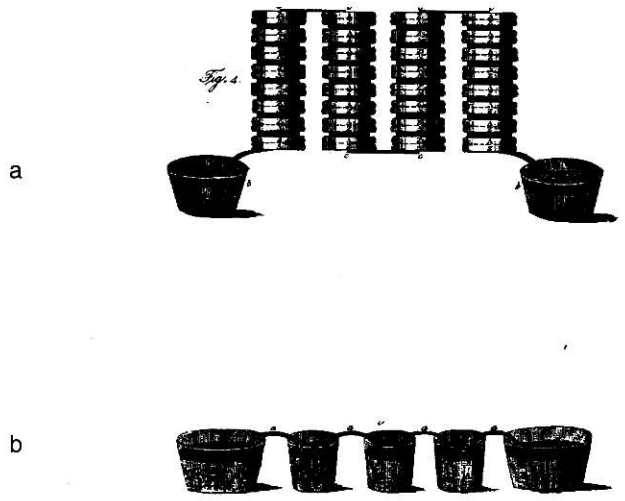

Figure 3

pile acts continuously, providing repeated shocks without being recharged by any external electricity; and 2) it consists solely of conductors of electricity. Volta drew from this difference two consequences. One was that he discovered the first "perpetual" source of electricity. Another one, less known, was that he found an explanation of the electric torpedo.

While Volta was convinced of having refuted animal electricity as a general feature of animal life, he could not challenge the existence of electricity in a few species of fish, such as the torpedo. In this case instead of denying the electricity of the torpedo, he wanted to explain it by physical factors. Being a reductionist, Volta aimed at explaining life phenomena by physical processes without bringing in any mysterious "vital forces".

Volta began with a critique of William Nicholson's theory of the electric organ of the torpedo, which compared it to a battery of Leyden jars. In Volta's view, since all membranes making up the columns of the electric organ are filled with fluids, they are comparatively good conductors. Since a Leyden jar cannot be made without an insulator, Volta concluded that electricity produced by the torpedo and some other fish cannot be static electricity. On the other hand, his pile consisted solely of conductors, and this, Volta supposed, could be the necessary model: the electricity of fish is galvanic, being produced by contact of organic substances of different nature. He indicates that shocks produced by a pile are comparable in strength to those of a languid torpedo, and that it can give repeating shocks. He even calls his apparatus an "artificial electric organ". This name, as well as the initial shape of the apparatus - a column - show that his preoccupation with imitating the electric organ of the torpedo was an essential element of his research program.

To convince his readers, Volta wanted them to succeed in repeating his experiments. Thus, he explains in detail how to build the apparatus and how to use it. In particular, he recommends to increase the number of couples and wet the fingers touching a pile, or, better still, to immerse a part of the hand in water that is connected to the pile. These tips are more

than empirical findings, they are closely correlated with his theory. Volta maintains that only a junction of two metals is an "electric motor", while the liquid itself is merely a conductor. Since one of the two metals attracts electricity more strongly than the other, each couple moves electricity in a certain direction, e.g. from zinc to copper. Thus, if several couples have the same orientation, their efforts combine, and the electricity moves faster: the more couples, the better. As to wetting the hand touching to the pile, it is to reduce its resistance. Using the whole hand instead of fingers serves the same purpose by increasing the area of its contact with the liquid. This idea provides a fine opportunity for physics teachers to expand their teaching of resistance to non-metal conductors.

Although Volta insisted that he had proven his theory of contact electricity earlier, it was the pile that made many scientists to turn to Volta's theory from that of Galvani. Apparently, they reasoned as follows: 1) the actions of the pile are electrical; 2) since its effect is nothing but a multiplied effect of a single couple, therefore a contact of two different metals creates electricity; and 3) the electricity created by a bimetal is the same whether it is detected by an electrometer or by a frog, thus Galvani's experiments were due to the "contact electricity" rather than "animal electricity". In fact, the last conclusion was not logical, since a circuit with a frog could have had both sources of electricity, but this detail went unnoticed. Yet, while securing the victory of contact electricity over animal electricity, the pile brought to life another powerful rival: the chemical theory.

The chicken-and-egg problem

The first objections came from England. Having seen the first part of Volta's paper before it was read in full at the Royal Society, several scientists constructed voltaic piles and began experimenting with them. In addition to the effects described by Volta, they found that a pile can produce various chemical phenomena. As the result, William Hyde Wollaston (1766-1828) and Humphrey Davy (1778-1829) suggested that, contrary to Volta's opinion, liquids play an active role in galvanic phenomena, and chemical reactions may be the cause of electricity rather than its consequence. Actually, some sort of a chemical theory was initiated by Giovanni Fabbroni in 1792, who saw the primary cause of galvanic phenomena in chemical reactions rather than electricity. However, after 1800, the meaning of the theory changed. To show the active role of the liquid, Davy performed the following experiment (Davy, 1800). In an iron-copper pile with water, iron is charged positively, but if water is replaced with sulfate of potassium it changes its charge to negative. He also created a pile of a single metal but of two different liquids: metal, cloth wetted with nitric acid, cloth with water, cloth with sulfate of potassium, same metal, nitric acid, etc. The acid and the alkaline at the ends of the pile were connected by paper strips moistened with water.

In his first responses to this criticism, Volta insisted that he had already proved in 1797 that a contact of different metals is an "electric motor". Soon Volta changed his tactics, claiming that the objections to his theory actually support it, including Davy's experiment with one metal and two liquids. In particular, he said, since a contact of any two different substances produces tension, and since the metal is positive relative to one liquid and negative relative to the other, both tensions move electricity in the same direction. As to the role of chemical reactions, since adding salt to pure water does not change the tension or polarity, chemical reactions are of no consequence to producing electricity. Volta agrees however to give chemical reactions a role in improving the conductivity of the pile: when an acid, for instance, attacks a metal surface, it adheres closer to it than water and thus diminishes the resistance of this contact.

The inconsistency of these two arguments is caused by Volta's usage of different detectors of electricity in the two cases. If the main criterion of the pile's power is tension as measured by an electrometer, then, indeed, different liquids produce about the same effect. However, when the power of a pile is measured by a shock or the rate of a chemical reaction, both of which are derivatives of current, changing the liquid does change the outcome. In fact, Volta himself confirms this by noting that adding salt to water made the shock much stronger.

His second argument would have been unassailable, if he could provide independent evidence that the conductivity of a liquid depends on the substance dissolved, its concentration, the area of contact, etc. However, for static electricity, such measurements were limited to comparing distilled water with sea water. As to galvanic electricity, no such data existed at all. In fact, eventually it became clear that the only way to compare the conductivity of two piles made of the same number of couples was by comparing an effect that depends on current, such as a shock received by the same person. Thus, Volta had no ground to assume that, given the same number of couples, the pile made of copper and zinc immersed in weak sulfuric acid acts more strongly than the one made of silver and zinc immersed in saline water, because the former pile has a greater conductivity than the latter.

Volta's theory of the pile dominated until the late 1830s, when the chemical theory began to gain ground. Interestingly, after 1802, Volta himself no longer participated in the debate.

Debating in science

What lessons can one draw from these debates? Perhaps the first impression would be that they do not fit the image people may have of a "scientific discussion", where the participants are attentive to the views of one another, passionless, and pursue no other goal than finding the truth.

In particular, one is struck by the rigid, uncompromising attitude of the participants, where each side claims to have the whole truth and insists on it until death. For instance, although there was some evidence that both "animal" and "contact" electricities exist, neither Galvani and Aldini, nor Volta were interested in a compromise.

Also, one may find it dishonest when scientists hide the shortcomings of the theory they favour (as Galvani with his Leyden

-jar model) or emphasise only those aspects of an experiment that supports this theory . For instance, Volta preferred to measure the "power" of a voltaic pile by its tension, because he had found tension to be independent of the chemical activity of a liquid. Davy, on the other hand, chose for that purpose the amount of gas released by the pile, because it depends on the liquid, which supported his theory of the active role of a liquid.

One may be surprised by logical inconsistencies in scientists' reasoning, such as rejecting "animal electricity" on the basis of experiments with a pile, or Volta's conclusion that zinc-copper couples produced the same electricity whether they have water between them or not.

Moreover, one may find some conclusions lacking any proof, such as Volta's statements that contacts of metals with liquids or of two liquids can move electricity. And bearing in mind that the latter statement was created with the sole purpose of explaining the "all-animal circuit", this should leave Volta's refutation of the frog's electricity hanging in the air.

All these circumstances can lead one to a conclusion that perhaps a scientific debate is not so different from a family dispute or a court trial where people try to win an argument rather than to establish the truth. Are scientists subjected to human passions when talking science? Apparently, yes, as one can see from the examples given above. However, before making the final decision that scientists very much resemble other human beings it makes sense to check whether an appearance of personal features does hide behind it objective (impersonal) factors. That impersonal factors exist follows from the fact that a similar pattern of behavior can be seen among scientists from different countries who argued about different matters.

One of them explains the simultaneous appearance of different theories. We have seen that the very nature of galvanic phenomena, where bio-potentials and electrochemical potentials coexist, allowed for either a physiological or a physical interpretation. Likewise, functioning of the pile was consistent with either a physical theory or a chemical one, for one could have attributed the origin of electricity to a mere contact of two different substances or to a chemical interaction between them.

Another reason accounts for scientists' stubbornness in adhering to a certain theory. When all competing theories are internally consistent and sufficiently supported by experiment, as those discussed above, selecting one of them is a personal matter. When neither theory explains everything, the choice of one is affected by various metaphysical beliefs, thus it cannot appear convincing to all. This means that clinging to one theory for a long time is no less "legitimate" than vacillating between the rival theories with each new experiment. Since some defects of each theory were obvious from its inception, apparently its partisans made their choice on the basis of the theory's positive contribution, with the hope that future research will resolve its difficulties. The same belief in the future appears to be behind the questionable methods of debating: the idea is that presenting a theory only at its best may attract talented people who will develop the theory further and free it of its shortcomings.

Still another factor may explain a shortage of compromises. One type of compromise involves recognising more than one cause of a phenomenon. This was rather unusual for the 19th century when scientists frequently relied on the "Occam's razor", or the principle of reducing the number of possible causes to a minimum. Sometimes, they succeeded in this, but in other cases they failed. Volta, for instance, was out of luck, for having initially admitted both "animal" and "contact" electricities, eventually he decided to drop the former. Another type of compromises involves creating a "compound" theory, which can be illustrated by the debate on the nature of voltaic electricity around 1850.

Finally, sometimes a failure of scientists to reach a consensus reflects the fact that necessary concepts had been not yet developed. For example, an uncertainty of arguments in the debate on voltaic electricity resulted from a lack of understanding of the role of the contact of two substances in their chemical interaction.

If a teacher is keen on investigative experimentation, this story supported by students' experiments may have practical consequences in teaching students how to go about creating a theory explaining their own investigative experiments. In particular, they learn that as long as a theory is internally consistent and explains several experiments, it has a right to exist even if it cannot account for other experiments. Here the concept of the "partial truth" is very useful: within the given range of phenomena studied and time spent the "partial truth" is the truth, and if future research modifies it, the original conclusion still preserves its validity within the original range. Although both Galvani and Volta believed they had discovered the whole truth, since their theories did not cover all known phenomena, they come under the above stated definition of the "partial truth". And if something was satisfactory (in the modern view) for Galvani and Volta, it must be satisfactory for students too. This means that in their investigations students should not fear to invent a false theory, provided they take care to make their conclusions sufficiently consistent and based on a sufficient number of experiments.

Naturally, students will soon discover the ambiguity of the word "sufficient": one cannot know in advance how many times to repeat each experiment and how many times to modify it in order to arrive at a "partial truth". Having learned this from their own experience students may become more critical of the certainty of the results of historical experiments and their validity as arguments in a theoretical debate.

Conclusion

Studying scientific controversies is one of the best ways for understanding of how scientists defend a new theory or choose between two theories. And historical cases are more suitable for this purpose than the modern one: a distance in time is important to separate essential from non-essential factors.

While the role of "human factors" in a scientific debate deserves special study, its absence should not preclude people from discussing the impersonal factors, which should come first, because it is they that make science different from other human enterprises.

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THE HARRIE MASSEY MEDAL

The Australian Institute of Physics, on behalf of the Institute of Physics, UK, seeks nominations for the 2000 Harrie Massey Medal, to be presented by the President of the IOP at the AIP Congress in Adelaide in December 2000.

Background: The Massey Medal was proposed at the AIP Congress in 1988 and established in 1990 as a gift of the Institute of Physics, UK, to mark the 25th anniversary of the founding of the AIP as a separate institution in 1963.

Sir Harrie Massey, born near Melbourne in 1908, had a distinguished career in the UK and in 1931, with Edward Bullard, published the first experimental evidence for electron diffraction in gases. He saw the potential of using direct rocket probes of the atmosphere layers and eventually, as Chairman of the British National Committee for Space Research he guided the entire UK space research programme. From 1960-64 he was President of the European Preparatory Commission for Space research. He was knighted in 1960.

Conditions: The prize is awarded every two years for contributions to physics or its applications made by an Australian physicist working anywhere in the world, or by a non Australian resident in, and for work carried out in, Australia. A lecture on the work for which the Medal is awarded is presented at Congress in the year of the award, and an article published in the Physicist. The recipient must be a member of the Australian Institute of Physics or the IOP.

Previous winners have been:

1990 Professor R Dalitz

1992 Professor D H Briggs

1994 Professor R Baxter, ANU

1995 Professor A D Buckingham, University of Cambridge

1996 Professor A Snyder, ANU

1997 Professor D Pegge, Griffith University

1998 Professor D Melrose, University of Sydney

Nominations as hard copy must reach Moira Welch, Honorary Secretary of the Institute, PO Box 283 Richmond NSW 2753, or as a Word 6, rtf file email attachment (m.welch@uws.edu.au) by Wednesday April 26th, 2000, accompanied by the following: A citation of not more than 300 words, written for a scientifically literate lay person (the citation is a crucial factor in the selection of the recipient); A short curriculum vitae for the Nominee: a full publication list is not required,10 of the Nominee's most significant papers should be listed; A list, with dates, of the Nominee's most significant contributions to their chosen field; Names and contact details of 3 referees.

Further details may be obtained from the Secretary, Ph 02 4578 4328.

Moira Welch,
Honorary Secretary,
Australian Institute of Physics
Ph (02) 4578 4328
Mailing address: PO Box 283 Richmond NSW 2753